Valence Bonds in Random Quantum Magnets

theory and application to $YbMgGaO_4$

Yukawa Institute, Kyoto, November 2017

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Massachusetts Institute of Technology

I.K., Adam Nahum, T. Senthil, arXiv:1710.06860

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Collaborators

Adam Nahum
(MIT -> Oxford)

T. Senthil
(MIT)

Spin-1/2 magnetic insulators are a playground for challenges in correlated quantum matter

Frustration: destabilizes classical magnetic order.

T=0 quantum paramagnets: valence bond liquids or solids

Spin-1/2 magnetic insulators are a playground for challenges in correlated quantum matter

Frustration: destabilizes classical magnetic order.

T=0 quantum paramagnets: valence bond liquids or solids

e.g. Kitaev honeycomb model (next talk) – already a challenge!

Aside: $K > 0$ chiral spin liquid has 10x stability to magnetic field

larger fields give intermediate gapless phase

Zheng Zhu, I.K., D.N. Sheng, Liang Fu, arxiv:1710.07595

Spin-1/2 magnetic insulators are a playground for challenges in correlated quantum matter

Frustration: destabilizes classical magnetic order.

T=0 quantum paramagnets: valence bond liquids or solids

Spin-1/2 magnetic insulators are a playground for challenges in correlated quantum matter

Frustration: destabilizes classical magnetic order.

T=0 quantum paramagnets: valence bond liquids or solids

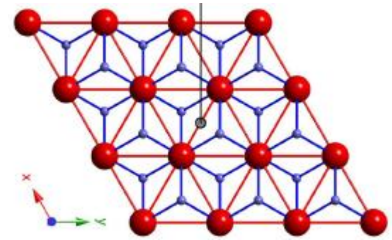
Quenched disorder: site impurities or bond-randomness

Spin glasses, irradiated high-Tc superconductors

Doped Mott insulators

This talk: interplay of quantum frustration and bond disorder

Experimental mystery: $YbMgGaO_4$



S=1/2 on triangular lattice – but no magnetic order

Strong spin-orbit-coupling (Yb^{3+}: $4f^{13}$)

Exchanges: J_1, J_2(?), XY, Kitaev… θ_{CW} = 4 K

Unusual magnetic phenomenology:

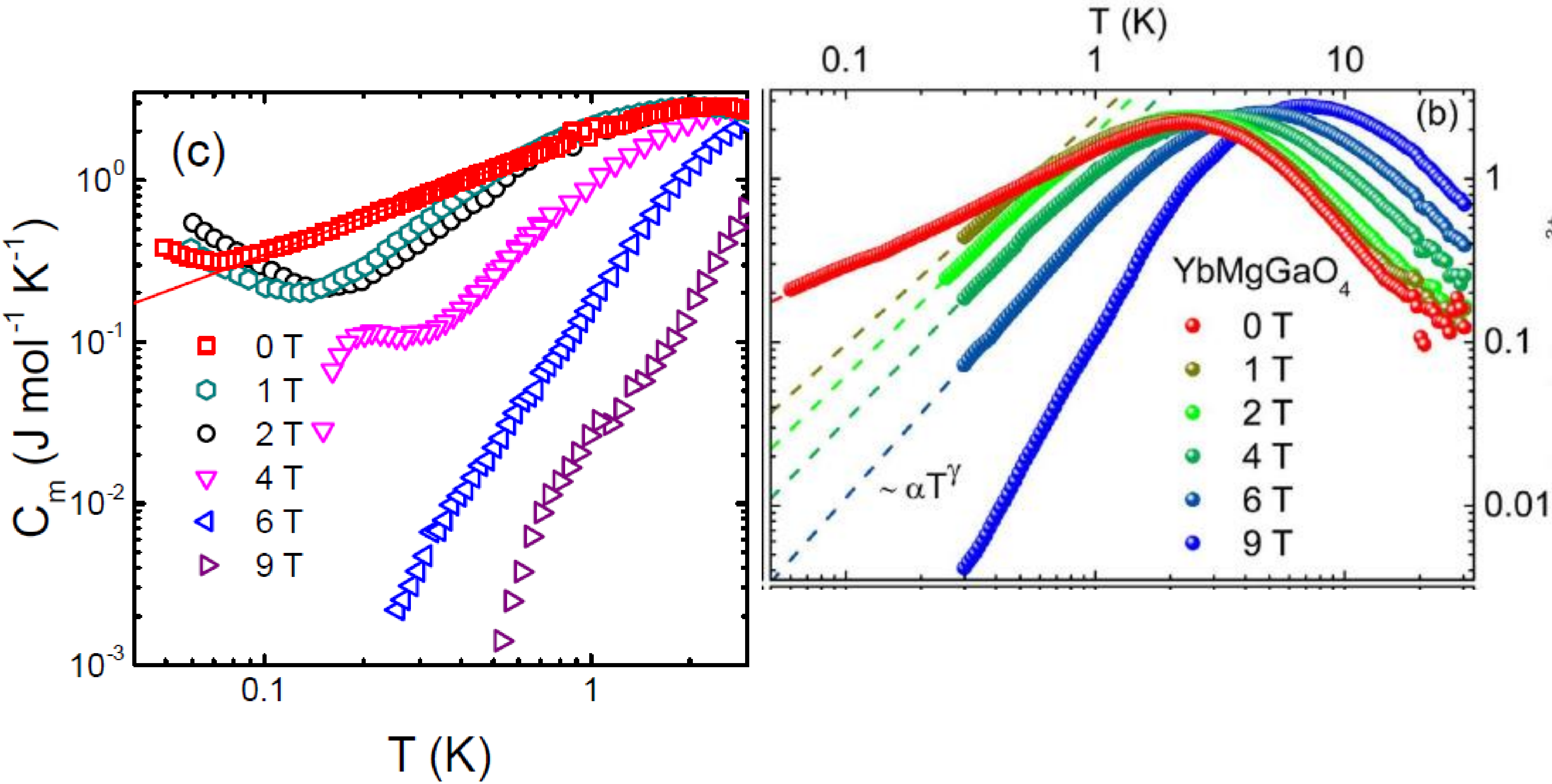
No spin order or glass (50 mK neutrons & μSR)

Anomalous heat capacity $C(T) \sim T^{0.7}$

but no corresponding thermal conductivity

Li *et al*, Sci. Rep. 5 (2015), Xu *et al*, PRL 117, Shen *et al*, Nature 540 (2016)

Low-temperature $C(T) \sim T^{0.7}$



Xu et al, PRL 117, 267202 (2016)
Li et al, Sci. Rep. 5, 16419 (2015)

How to understand this unusual phenomenology?

$C(T) \sim T^{0.7}$:

interpreted as "spinon Fermi surface" (Gang Chen *et al.*)

missing signatures of itinerant spinons

Ingredients for an alternative hypothesis:

Frustration: Geometrical & spin-orbit-coupling

capture via non-magnetic "valence bonds" basis

+

Disorder: Magnetic exchanges with random energies

due to Mg/Ga mixing in the non-magnetic layers

Say **frustration** prevents magnetic order: describe clean magnet in **valence bond** basis, then add **bond-randomness disorder**

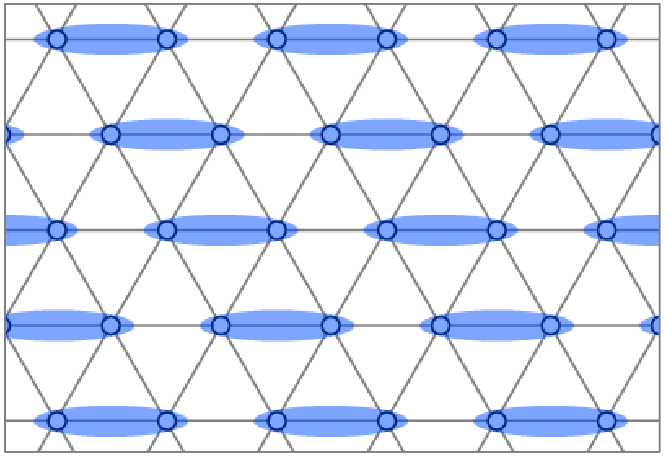
$$H = \sum J \vec{S} \cdot \vec{S} \qquad J \rightarrow J + \Delta J_{ij}$$

Even in limit of weak disorder $\Delta J \ll J$

linear coupling to *valence-bond-solid* order (Imry-Ma)

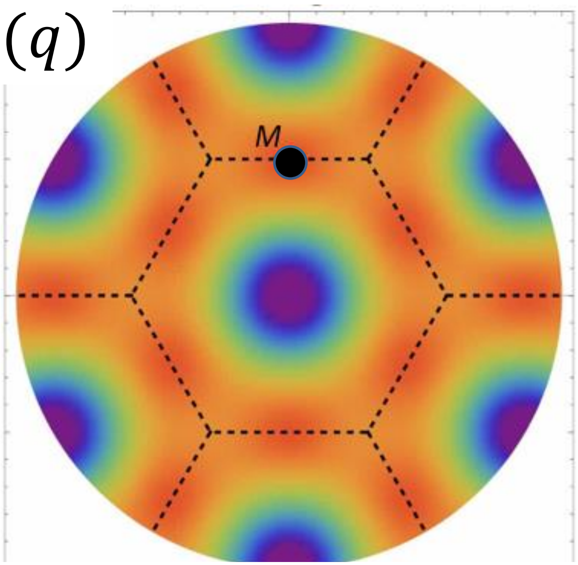
→ splits VBS into domains of short-ranged singlets

VBS: *T*=0 paramagnet w/ broken lattice symms

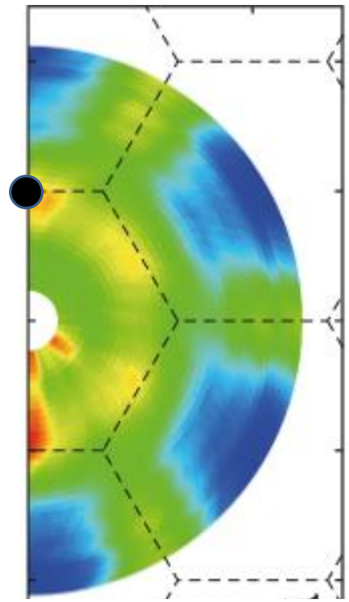


Random short-ranged singlets are a good starting point

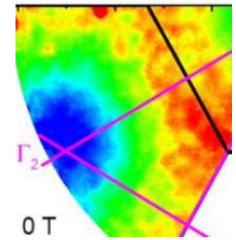
$S(q)$



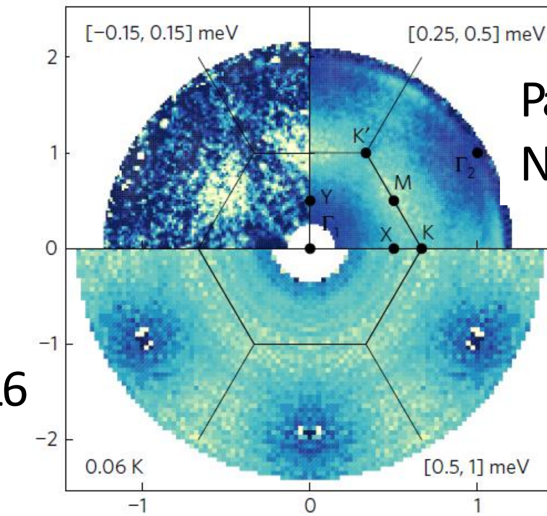
Randomly oriented
short-ranged singlets



Shen *et al*, Nature 2016



Li *et al*,
Nat Comm 2017



Paddison *et al*,
Nat Phys 2017

But: frozen valence bonds → gap.

What gives gapless $C(T) \sim T^{0.7}$?

Competition between disorder and valence bonds *necessarily* leads to low-energy spin excitations: strong-randomness network of spin-1/2 emerges

Rough sketch of the argument:

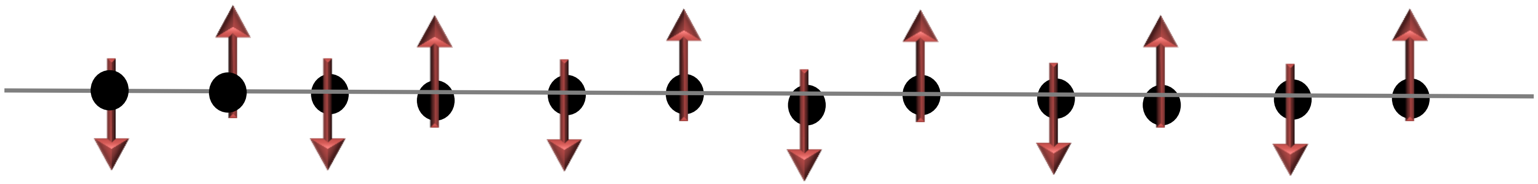
(1) Weakly disordered VBS: vortices carrying spin-1/2

(2) Stronger disorder: defect instability of pinned singlets

(3) Disordered Lieb-Schultz-Mattis conjectures

(4) Application to $YbMgGaO_4$: $S(q,\omega),\kappa(T),C(T)$ & B-field

Warm up: 1D spin-1/2 chain
spontaneous dimerization + disorder



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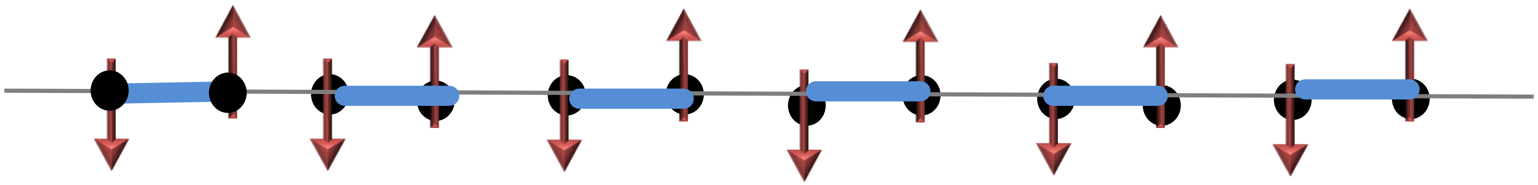
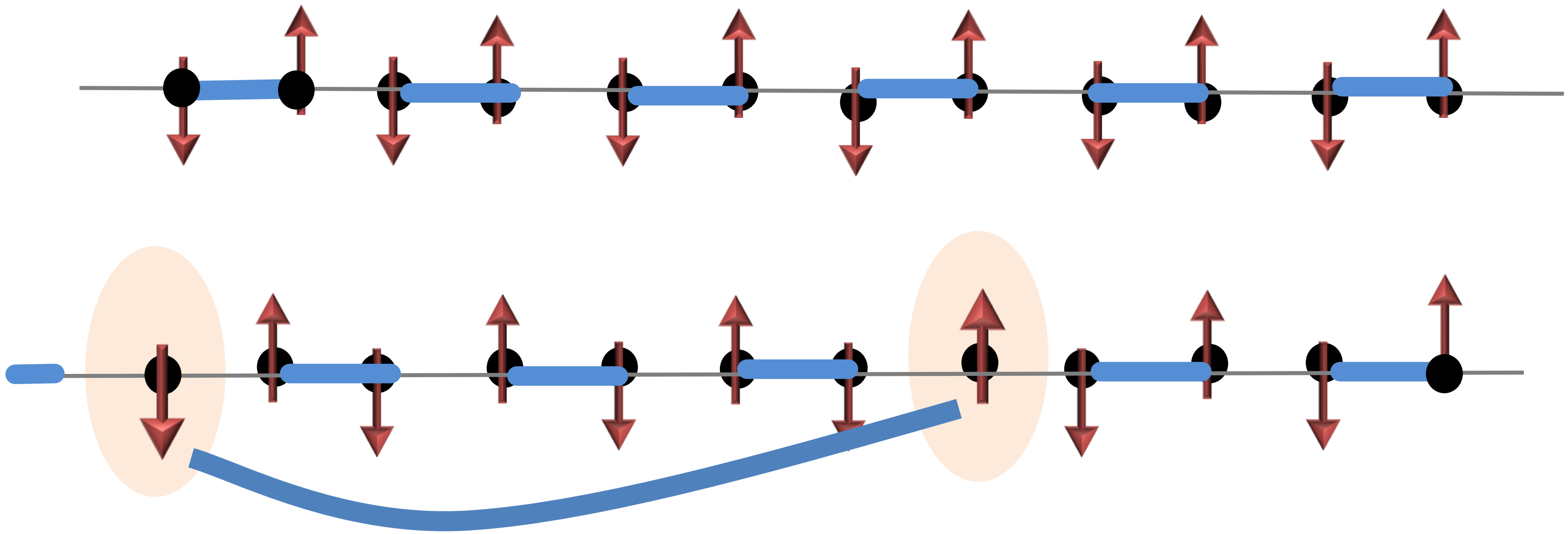


Clean system in dimerized ("VBS") phase

Adding disorder breaks up domains

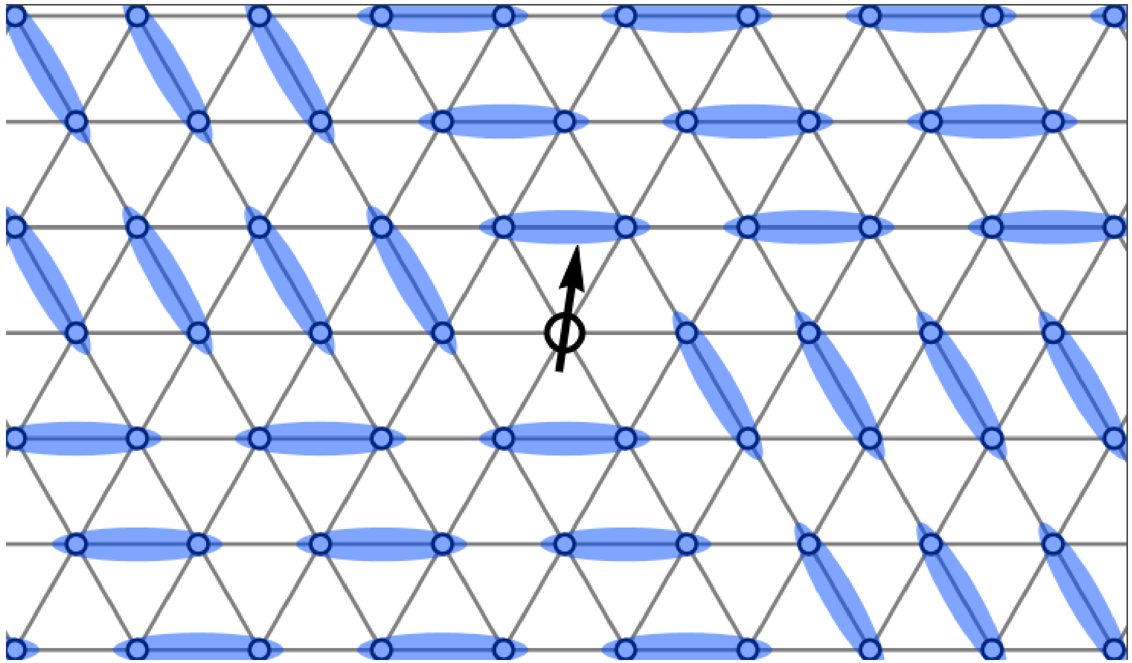
Warm up: 1D spin-1/2 chain spontaneous dimerization + disorder



Domain wall carries single S=1/2

→ RG flow to 1D random-singlet phase (Fisher '94)

2D vortices with spin-1/2 modes



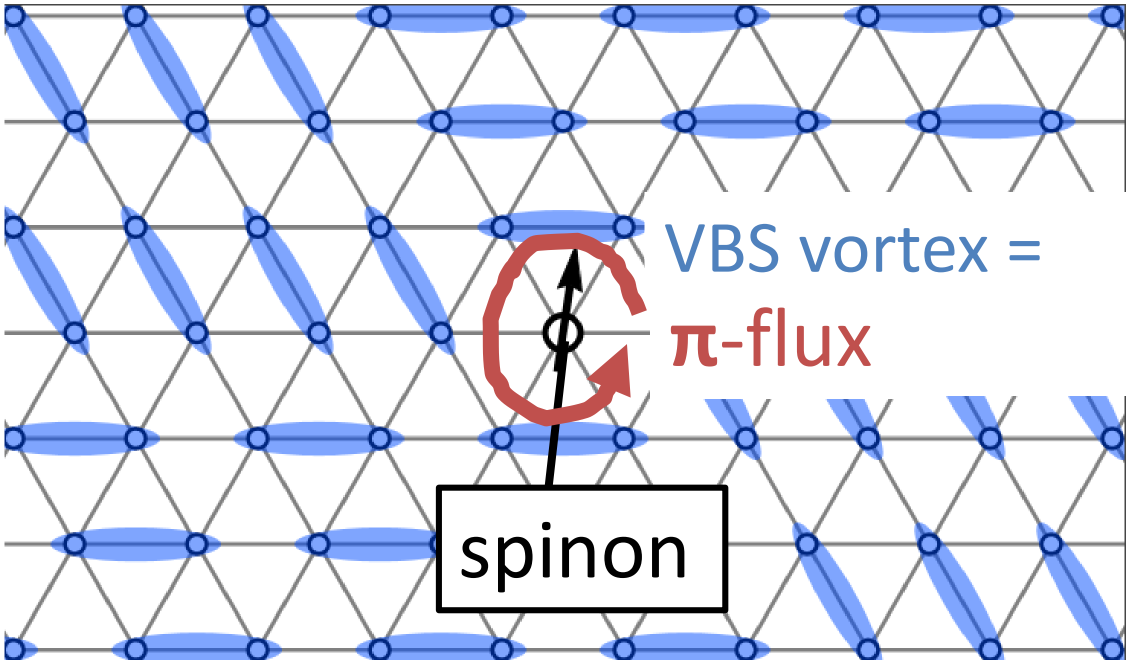
Interpret via Z_2 spin liquid: condense vison vector $\boldsymbol{v}$

VBS order parameter = $\boldsymbol{v}^2$

$\boldsymbol{v}^2$ headless vector → Z_2 vortices

Z_2 vortex = vison Z_2 gauge field π-flux

Vortices carry spin-1/2 modes



Interpret via Z_2 spin liquid: condense *vison* vector $\boldsymbol{v}$

VBS order parameter = $\boldsymbol{v}^2$

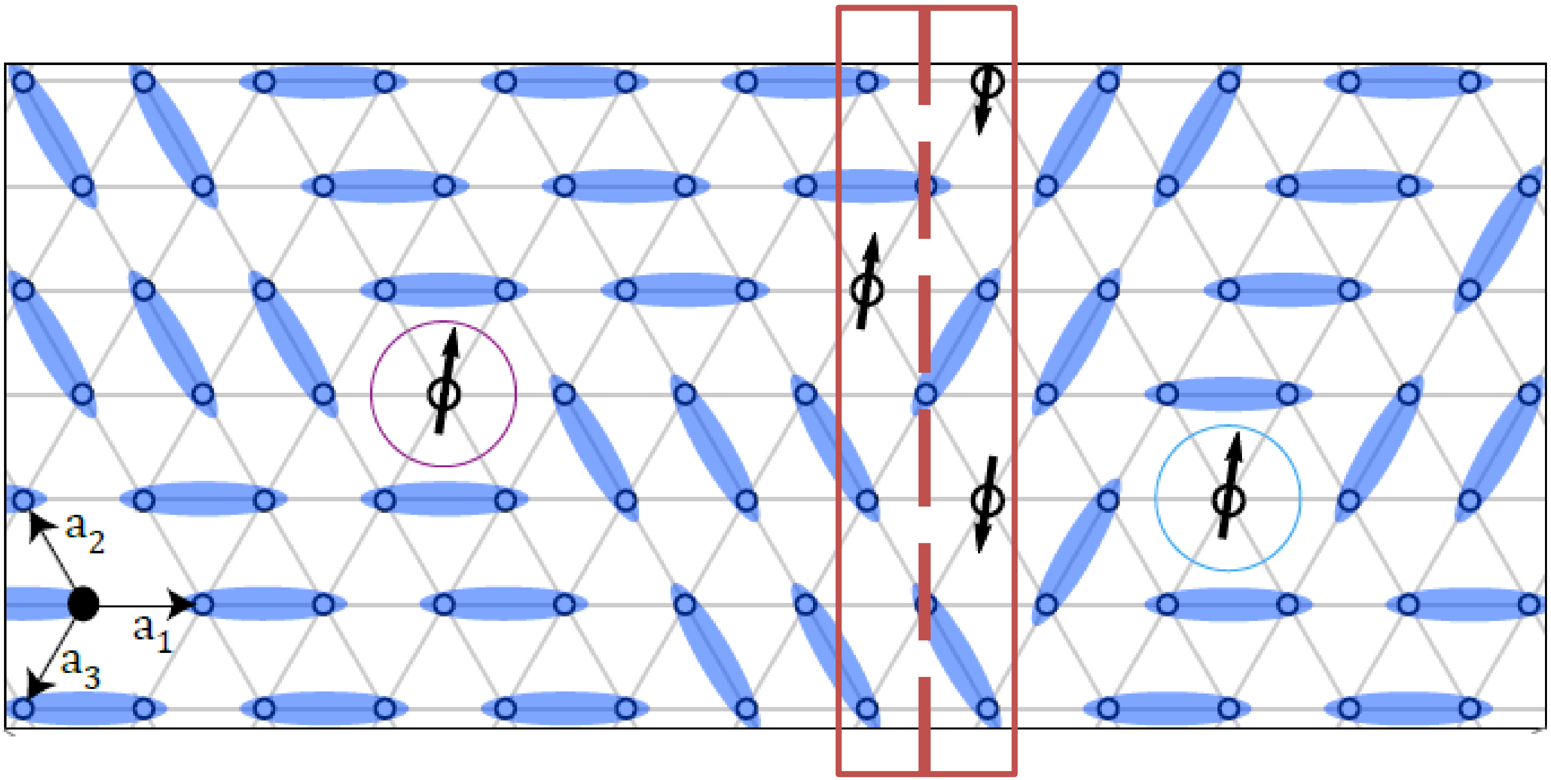
$\boldsymbol{v}^2$ headless vector → Z_2 vortices

Z_2 vortex = vison π-flux = spin-1/2 *spinon*

Details for triangular lattice columnar-VBS:

domains cluster into "superdomains"

superdomain-walls carry S=1/2 chains



a superdomain maps to square lattice VBS: Z_4 vortices

RG flow arises from weak disorder

Clean-system VBS domain

Imry-Ma lengthscale Exp$[\Delta^{-2}]$

Random network of vortex S=1/2

Strong disorder RG

Long-range singlets + clusters

Ultimate fixed point (spin glass?)

Are the S=1/2 vortices always natural?
Can stronger disorder pin singlets into a short-ranged "valence bond glass"?

(1) Weakly disordered VBS: vortices carrying spin-1/2
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Enforced nucleation of S=1/2 defects

Spin-1/2 defects cost energy. Are they necessarily nucleated by disorder?

Limit #1, Imry-Ma weak disorder: topological defects appear between large domains

Limit #2, regime of intermediate disorder:

VBS pattern selection scale << Disorder << Clean-system spin gap

Map to random-energy dimer model

but now allow monomers/defects

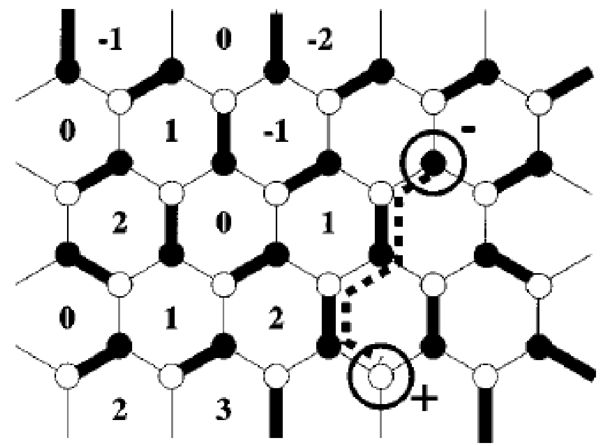
Enforced nucleation of S=1/2 defects

Classical dimer model w/ random energies on bonds
with allowed monomers/defects

Bipartite lattices: any disorder will nucleate defects

Zeng-Leath-Fisher (PRL 1999)

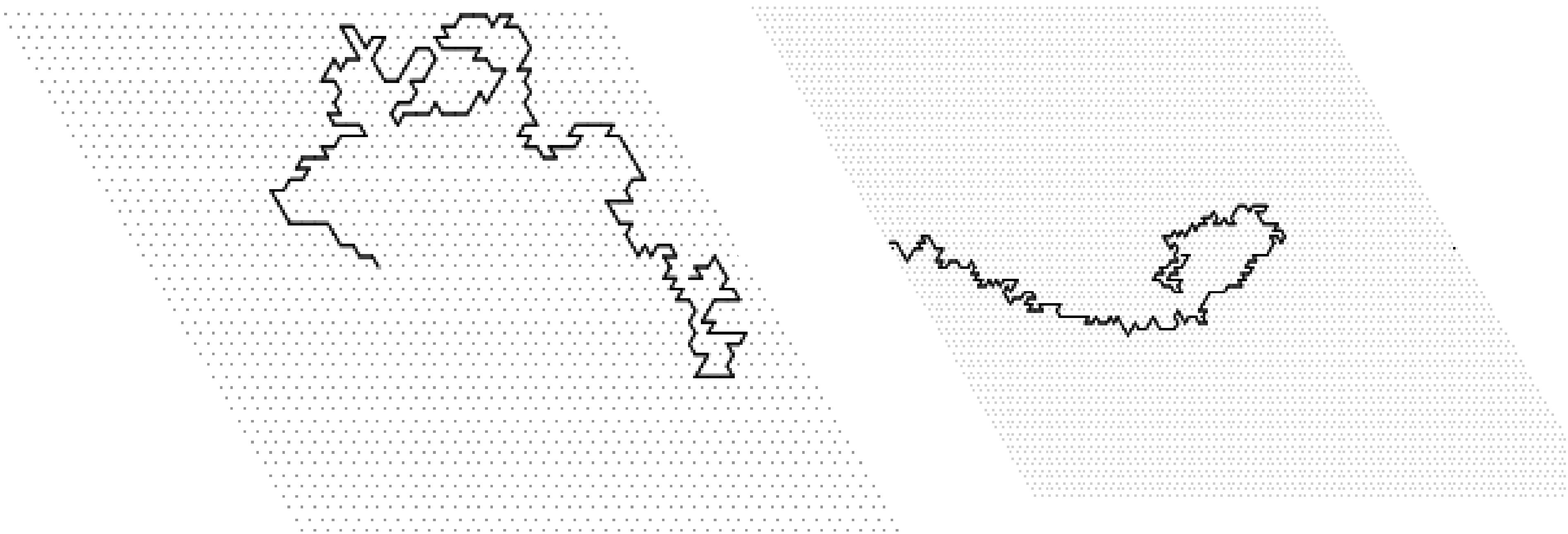
Middleton (PRB 2000)



Non-bipartite case unknown;

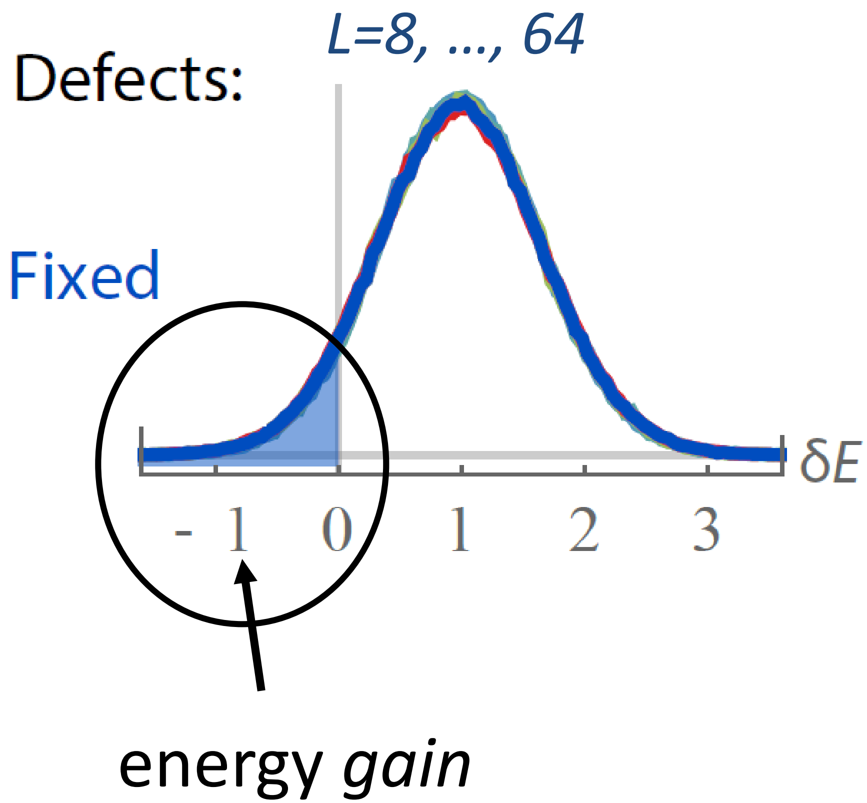
Study on triangular lattice

(Fractal defect strings confirm mapping to Ising spin glass)

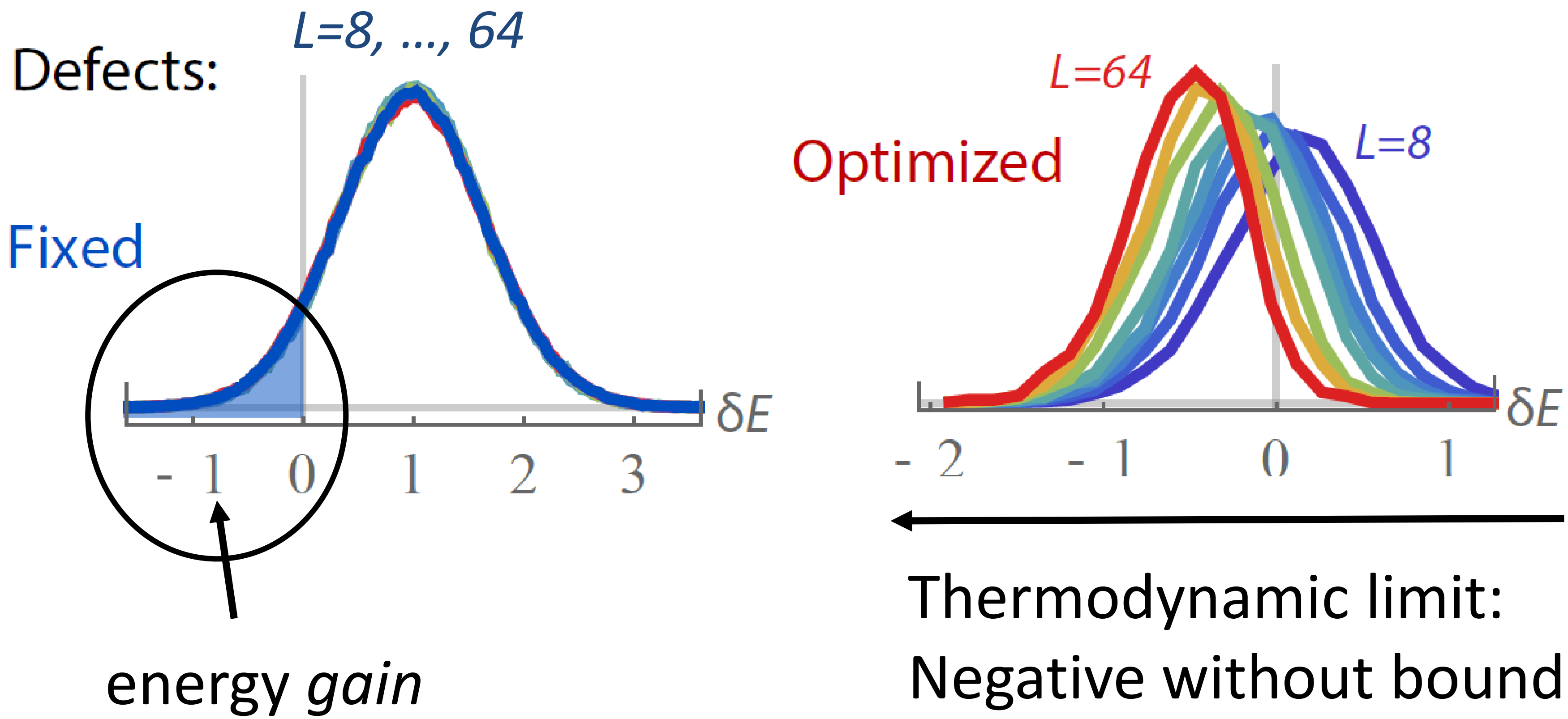


Fractal dimension $d_f = 1.28$

Energy distribution for two fixed defects



Energy distribution for partially-optimized defects



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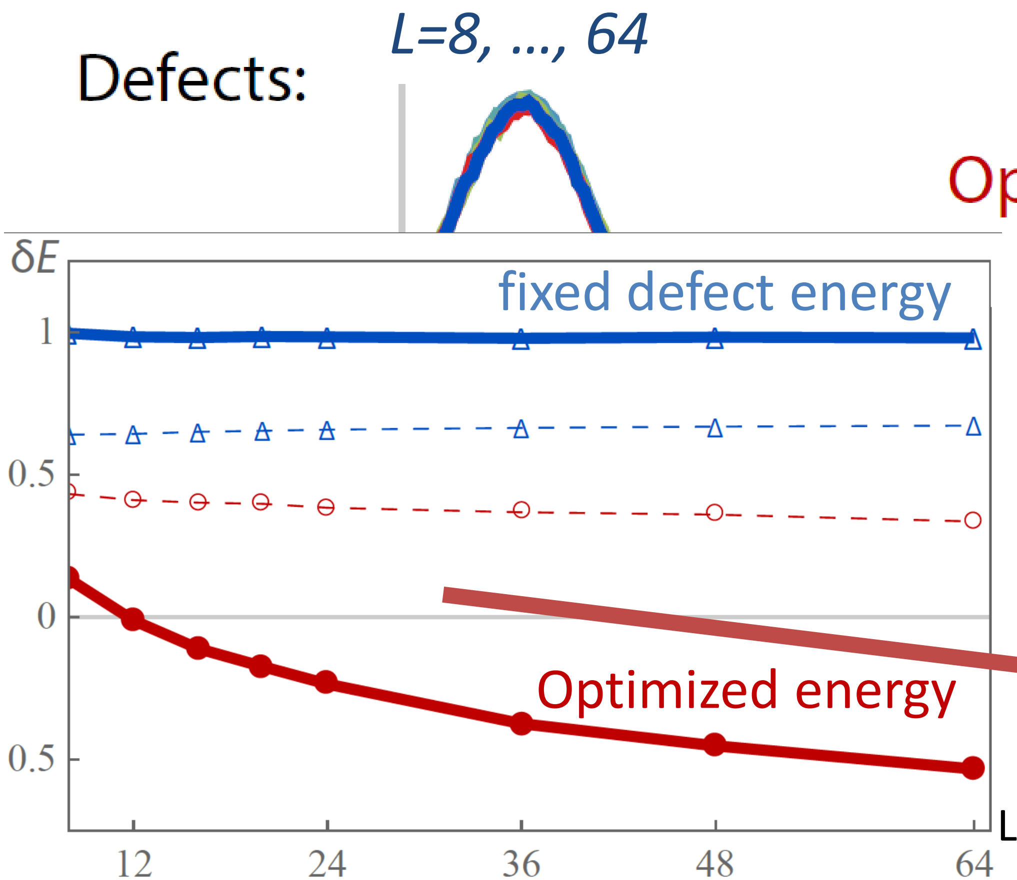

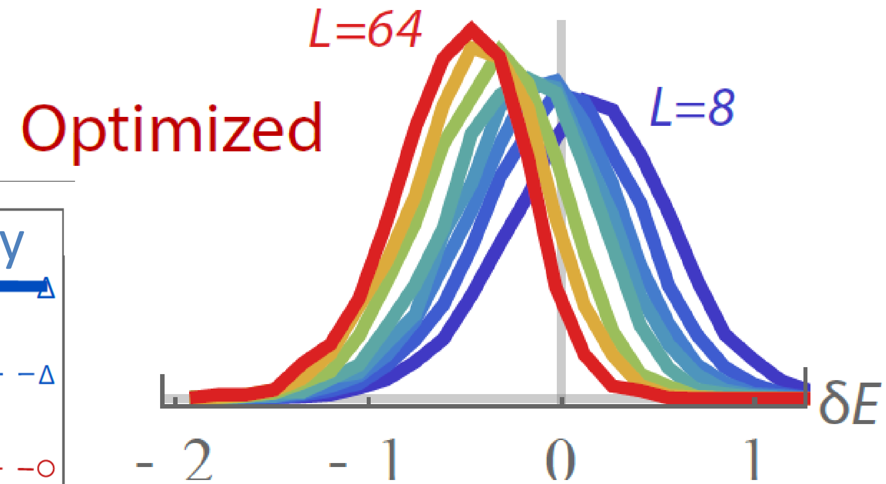

Divergent energy gain from disorder: defects will always nucleate

Adding weak/stronger disorder to destroy VBS-symmetry-breaking / spin-liquid *necessarily* nucleated gapless spin excitations.

Is this a general principle?

(1) Weakly disordered VBS: vortices carrying spin-1/2

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(3) Disordered Lieb-Schultz-Mattis conjectures

(4) Application to $YbMgGaO_4$: $S(q,\omega)$,$\kappa(T)$,$C(T)$ & B-field

Is this a general principle?

Naively expect disordered state to be featureless, spin-gapped

But vortices/monomers with spin-1/2 appeared!

Recall Lieb-Schultz-Mattis-Hastings-Oshikawa theorem (*LSM*):

S=1/2 per unit cell $\Longrightarrow$ featureless states must be gapless

Here: **LSM** with **disorder**? gapless **spins**?

Disordered-LSM conjectures

Given spin rotations and *statistical* translations
with S=1/2 per unit cell

Conjecture restrictions for featureless ground states
(if no symmetry-breaking/topological order)

2D: must have gapless *spin* excitations
(e.g. long-range singlets)

1D: spin correlations at least algebraically-long-ranged

General argument in 1D (Adam Nahum)

3D: forthcoming

[alternative formulations via quantum information]

What are implications of this enforced RG flow?

Can this physics be observed?

(1) Weakly disordered VBS: vortices carrying spin-1/2

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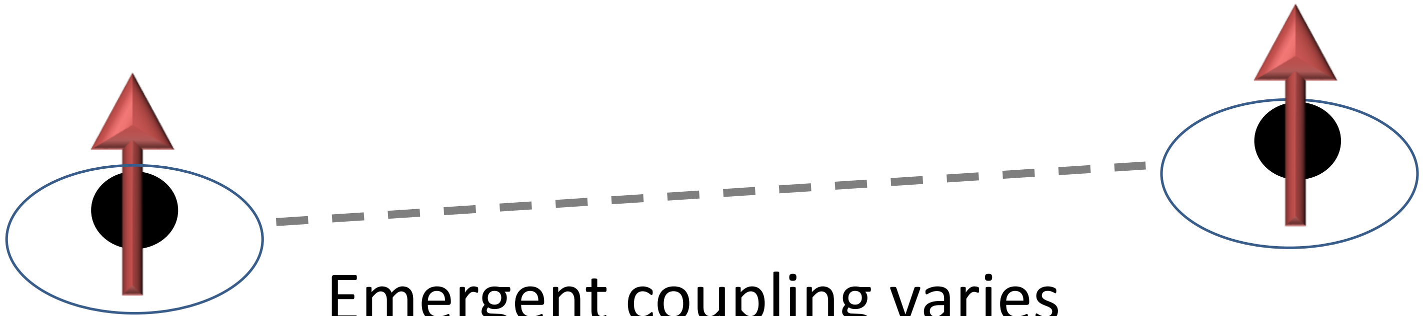
Random network of spin-1/2 emerges: Shows random-singlets and some spin freezing



Emergent coupling varies exponentially with separation

→ Power-law density of states (as in Si:P)

2D random-singlet phase

ultimate fixed point likely has frozen moments

$YbMgGaO_4$: $C(T) \sim T^{0.7}$

$YbZnGaO_4$: $C(T) \sim T^{0.6}$

both: anomalous low-T spin freezing

Ma *et al.*
1709.00256

Relevance to $YbMgGaO_4$: Summary, Predictions

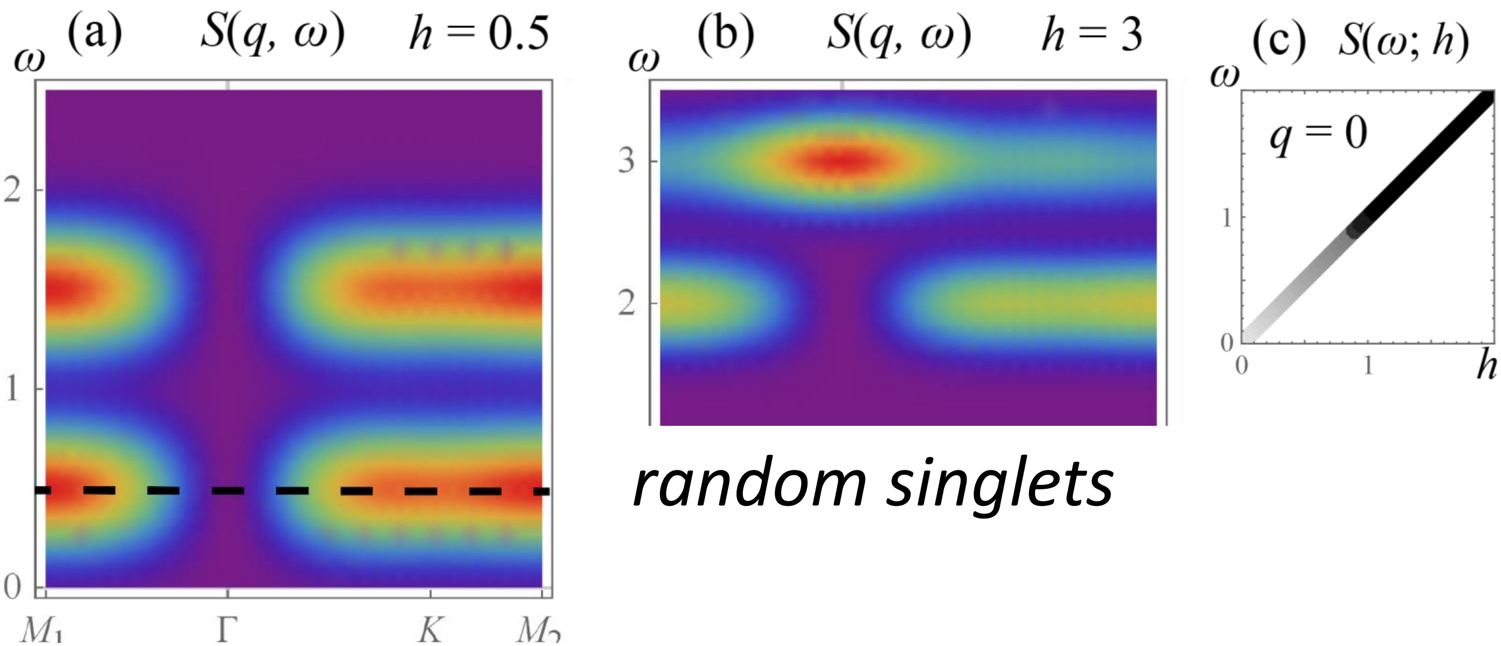
Summary, “post-dictions”:

1. No magnetic order
2. Short-ranged singlets at energies of order *J*
3. Power-law density of states at low energies, $C(T) \sim T^{\alpha}$

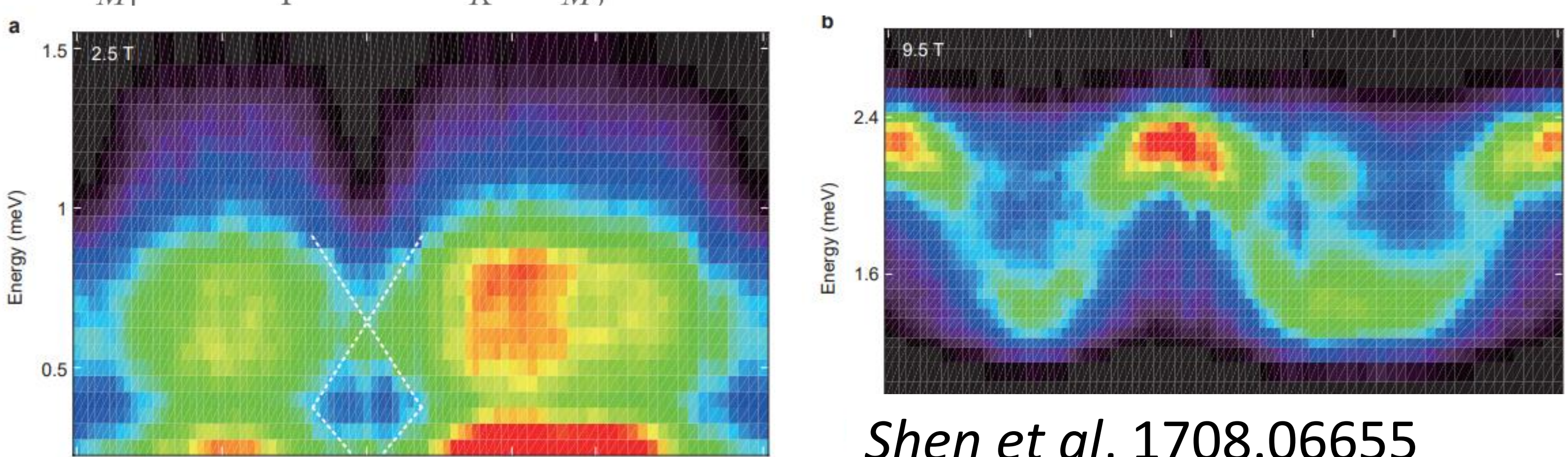
Nontrivial predictions:

1. Thermal conductivity $\kappa(T) \sim T^{1.9}$ (glassy phonons) ✓
2. Possible short-ranged VBS order [q=*M*] ✓
3. Some glassy freezing at *T*=0 ✓
4. Behavior in a magnetic field: $\kappa(T), C(T)$ ✓ and $S(q, \omega)$ ✓

Recently measured $S(q, \omega)$ in magnetic fields consistent with random singlets



random singlets



Shen et al, 1708.06655

Conclusions: Frustration + Disorder

RG flow to random network of spin-1/2

Anomalous power-laws

Enforced by disordered-LSM?

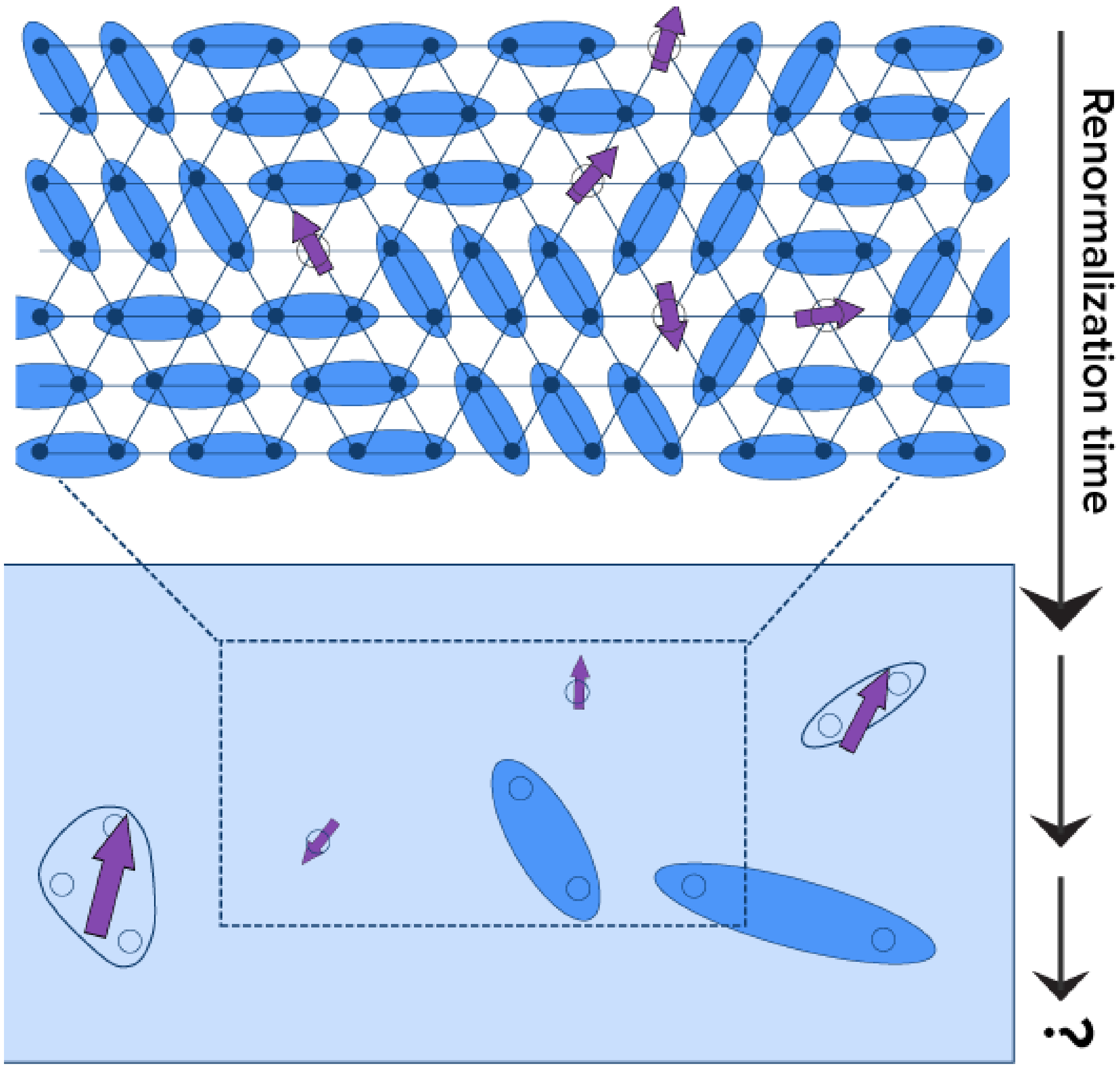
Outlook:

Spin liquids + defects

Disordered-LSM proofs

Numerical access

Other materials



For more, see arXiv:1710.06860